

Precise Time and Time Interval, Astrometry and Astrophysics

Kenneth J. Johnston
U.S. Naval Observatory
3450 Massachusetts Ave., NW
Washington DC 20392-5420
phone: (202) 762-1513 fax: (202) 762-1461 email: kjj@astro.usno.navy.mil

Award Number: N0001499WR30018
<http://www.usno.navy.mil/>

LONG-TERM GOAL

This program develops, implements, and tests, on telescopes and precise time systems, technologies for the determination of the positions and motions of celestial bodies, the motions of the Earth, and precise time in order to provide the astronomical and timing data required by the Navy and other components of the Department of Defense (DoD) for navigation, precise positioning, command, control, and communications, as well as developing sensor systems for surveillance. The primary goal is to improve the accuracy, quantity, timeliness, and reliability of the operational support provided by the U.S. Naval Observatory (USNO) to DoD in the areas of precise time and time interval, Earth rotation and orientation, and inertial reference frames based on star, planet, and extragalactic source positions. Further technologies will be developed to improve sensor technologies for surveillance, targeting, and navigation.

OBJECTIVES

The USNO Mission, as the only U.S. institution engaged in the practical application of astrometry and timekeeping, is to provide DoD with precise time and celestial position data and also to promulgate such data as directed by public law through the publication of the astronomical ephemeris. The R&D supported by this area allows the USNO to fulfill its operational mission responsibilities in a field, which has an ever evolving technology in sensors, communications, systems control, and analysis. Specific objectives of this program include:

- Improvement of the U.S. Master Clock systems both in Washington and at Schriever AFB, the master control station for GPS, by evaluating and incorporating new types of clocks, real-time clock monitoring systems, and time scale algorithms for clock ensembles.
- Evaluation and refinement of various time transfer (clock synchronization) techniques especially using GPS in order to provide and sustain a tightly coupled worldwide DoD time system.
- Improvements to the fundamental ephemerides, which are the bases for positions of solar system bodies and the fundamental stellar reference system.
- Improvements to the algorithms for artificial satellite motions and their orbits especially in the area of GPS orbits in order to improve the accuracy of UT1 and polar motion.

Report Documentation Page			Form Approved OMB No. 0704-0188	
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.				
1. REPORT DATE 30 SEP 2003		2. REPORT TYPE		3. DATES COVERED 00-00-2003 to 00-00-2003
4. TITLE AND SUBTITLE Precise Time and Time Interval, Astrometry and Astrophysics		5a. CONTRACT NUMBER		
		5b. GRANT NUMBER		
		5c. PROGRAM ELEMENT NUMBER		
6. AUTHOR(S)		5d. PROJECT NUMBER		
		5e. TASK NUMBER		
		5f. WORK UNIT NUMBER		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) U.S. Naval Observatory,,3450 Massachusetts Ave., NW,,Washington,,DC, 20392		8. PERFORMING ORGANIZATION REPORT NUMBER		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S)		
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)		
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited				
13. SUPPLEMENTARY NOTES				
14. ABSTRACT This program develops, implements, and tests, on telescopes and precise time systems, technologies for the determination of the positions and motions of celestial bodies, the motions of the Earth, and precise time in order to provide the astronomical and timing data required by the Navy and other components of the Department of Defense (DoD) for navigation, precise positioning, command, control, and communications, as well as developing sensor systems for surveillance. The primary goal is to improve the accuracy, quantity, timeliness, and reliability of the operational support provided by the U.S. Naval Observatory (USNO) to DoD in the areas of precise time and time interval, Earth rotation and orientation, and inertial reference frames based on star, planet, and extragalactic source positions. Further technologies will be developed to improve sensor technologies for surveillance, targeting, and navigation.				
15. SUBJECT TERMS				
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT Same as Report (SAR)	18. NUMBER OF PAGES 8
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified		

- Improvement in the models and algorithms used for Earth rotation and orientation predictions to fulfill DoD systems autonomy requirements.
- Improvements to astronomical reference frames based on star, planet, and quasar positions, including increases in precision, benchmark density, and inertial stability.
- Development of radio/IR/optical interferometry and charge coupled device (CCD) technology for precision astronomical measurements, including satellite tracking applications, and expansion of precision star catalogs to the infrared wavelengths by exploiting IR technology.

APPROACH

Improvements to the precision of the Master Clock are being developed to meet future needs in precise positioning for targeting. The development of atomic fountain technology is underway to improve the precision of the Master Clock. A cesium fountain was first demonstrated. The cesium fountain has met its short-term performance goals, and we have analyzed the medium- to long-term performance up to several days. The existing R&D device has been completed and is performing long-term evaluations that are referenced to the USNO Master Clock. Work is now progressing on the more heavily engineered R&D fountain. This device is being built with rubidium atoms (to lower collisional frequency shifts). We have investigated alternate laser synthesis methods for trapping and cooling the atom, and have built the microwave interrogation regions and much of the vacuum chamber.

Various methods of time transfer—worldwide clock synchronization to UTC (USNO)—must be evaluated. DoD users operationally get their time directly from GPS (UTC (USNO)) at the 30 to 1000 nsec level. However other techniques can yield substantial improvement. GPS common view provides absolute synchronization at the 10 nanosecond level, but other methods, including carrier phase GPS tracking, laser reflection, fiber transmission, global broadcasting, the WAAS, and two-way radio transmissions, in some cases have demonstrated the ability to provide synchronization at the nanosecond, or better, level. All of these techniques need further refinement for use in operational systems.

Technological advances in the performance of imaging detectors (such as CCDs: Charge Coupled Devices) are closely followed and investigated to determine possible applications that would lead to improved astrometric performance. In recent years, such changes have led to significant improvements in detector dynamic range, lower noise characteristics, and faster read-out, resulting in improved position determination.

In the infrared, panoramic imaging detectors are getting larger and their use for surveys and astrometry in the infrared has been demonstrated by astronomers at USNO's Flagstaff Station. Plans are now underway to develop an even larger and more efficient camera using detectors currently under development. USNO astronomers have been involved in key positions in the design, specification, fabrication, testing and evaluation of the last two generations of large-scale infrared detectors.

USNO is involved in a highly successful celestial survey called the Sloan Digital Sky Survey (SDSS). This survey will eventually determine very accurate star positions for all stars brighter than about magnitude 22 for a significant fraction of the sky. The technique is to use a modest-sized telescope (aperture of 2.5m), with a wide field of view (seven square degrees), and which employs a powerful

imaging camera with an array of over 50 CCDs in the focal plane. Innovative observing techniques are used to gather 30 GB of data an hour, and sophisticated software pipelines process the data and determine many parameters (positions, brightnesses, colors, etc.) for all detected objects.

A new wide-field telescope at the Flagstaff Station is undergoing shake-down test and evaluation. A new camera for the telescope, designed and assembled in-house, is nearing completion. It will employ six large-format (2048x4096 pixels) CCDs which will allow the telescope to rapidly survey the sky in a number of passbands from the near ultraviolet to the near infrared.

Research on the capability of a CCD focal plane to make precise measurements under space conditions has been and continues to be supported under 6.2 funding.

WORK COMPLETED

The short term performance of the cesium fountain has been improved to levels as good as $1.5 \times 10^{-13}/\sqrt{\tau}$. Work on many aspects of the device has resulted in continuous operation for up to 30 days. In addition, operation has been demonstrated with a steered hydrogen maser as the output of the fountain. When operating with a steered output, the fountain detected and removed the drift of the maser at the level of better than $2 \times 10^{-16}/\text{day}$.

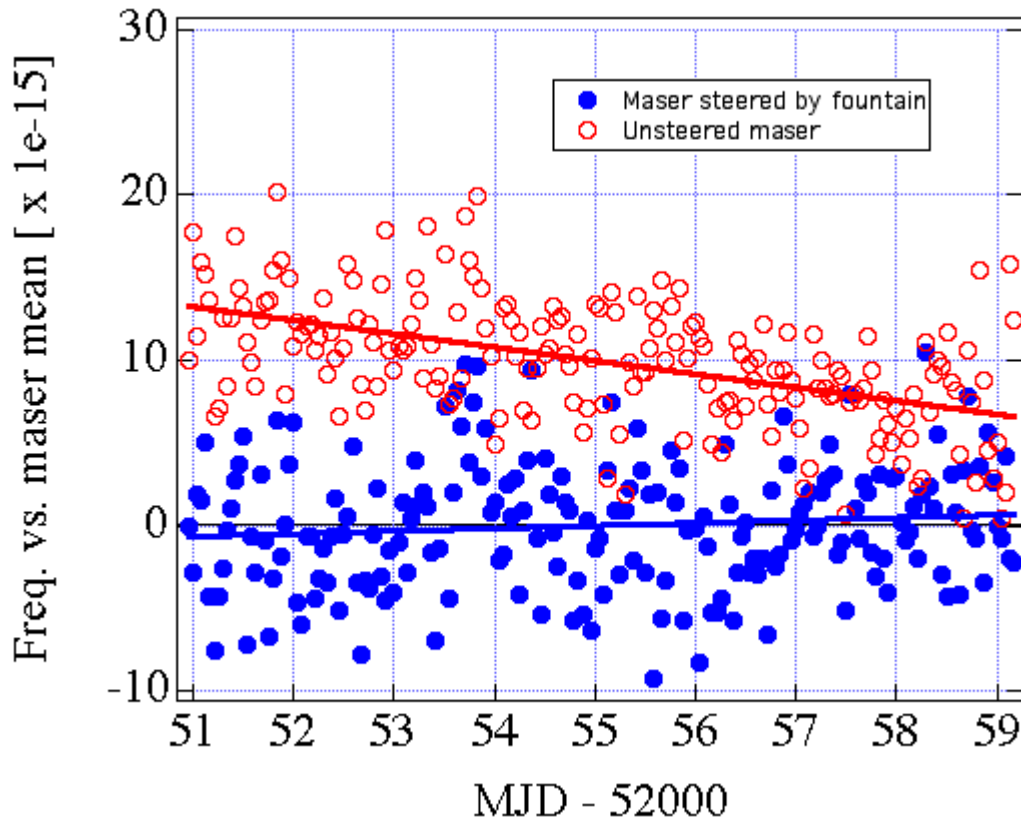
All major elements of the design of the rubidium fountain have been completed. All major technological approaches have been frozen in the design. We have identified primary and secondary approaches to the laser synthesis.

Many of the subsystems have not only been designed but have been produced and tested. We have developed improved microwave cavity coupling systems, modular laser light delivery and collection systems, modular electronic systems, and improved magnetic shields. These designs will allow for the device to fit in a deployable package roughly the size of three equipment racks. The resulting engineering prototype will be the basis of our operational buildout.

The program in GPS carrier phase time transfer has been delayed due to funding constraints.

USNO's work with NAVSYS to develop a 16 element phased array antenna working with a dual frequency 12 channel GPS P/Y code time monitor station receiver has been stopped due to loss of 6.2 funding. The addition of the phased array antenna will allow for much improved receiver measurement noise because of an almost 12 dB increase in S/N and much reduced multi-path due to the directional nature of the antenna. This system should also allow for real time GPS carrier phase ambiguity resolution that should lead to picosecond level time transfer. The antenna and receiver were delivered to USNO in Sept 02. In FY03, tests will be underway to evaluate its performance.

FY03 was another successful observing year for SDSS. Nearly 6,000 square degrees of the northern galactic hemisphere have now been observed and spectra have been obtained for about 350,000 objects in the north. All Survey regions in the southern Galactic hemisphere have now been observed, both imaging and spectroscopy. A major public release of data occurred this year in which data for over 53 million unique objects was presented, along with spectroscopy of nearly 200,000 objects.



Demonstration of the Cs fountain steering out the drift of a hydrogen maser. When operating with the steered output, the fountain detected and removed the drift of the maser at the level of better than 2×10^{-16} /day. The two data sets are offset vertically for clarity.

The USNO's contributions to SDSS, mainly in the astrometric reduction and analysis, have become reliable, robust, and even routine. The performance far exceeds the original requirements, and star positions are typically better than 50 milliarcseconds per coordinate.

In addition to these excellent astrometric results from SDSS, the project continues to deliver first-rate science in virtually all arenas of optical astronomy, from the studies of the largest scales in the universe to those of nearby solar system objects.

RESULTS

The cesium fountain has demonstrated continuous operation with a steered output for up to 30 days with a short-term stability of 1.5×10^{-13} at one second. Major portions of the rubidium fountain design are done, and all subsystem designs completed.

The SDSS astrometry uses the USNO CCD Astrograph Catalog (UCAC) to determine the positions of objects on the sky. This new catalog is now over 80% complete and reaches to fainter limits than previous astrometric catalogs. This allows for much cleaner astrometric calibrations of faint stars discovered in new surveys. UCAC sky coverage should reach 100% in late spring of 2004, and SDSS observations will then be re-calibrated.

To date, SDSS has discovered and confirmed approximately ten Quasi-Stellar Objects (QSOs or quasars) per square degree throughout the observed survey area. These extremely distant objects show no detectable motion across the sky (proper motion). Current astrometric catalogs rely upon relatively near-by stars, which move across the sky with time, and result in a degradation of the positional accuracy. Quasars discovered with SDSS have accurate positions and no motions, thus providing an “inertial reference frame” of astrometric sources free from these effects.

SDSS star positions have been compared with those of other contemporary surveys, as well as with surveys from years to many decades ago. These comparisons allow for a better determination of the changing positions of stars with time and thus lead to more accurate positions for catalog stars both now and into the future. These improved positions and predictions are not only important for astrometry, but also contribute significantly to an understanding of stellar motions within our Milky Way Galaxy and reveal important clues about its formation history.

The SDSS five-year survey will be complete on June 30, 2005. Plans are underway to employ the unique telescope and instrumentation to scan more of the northern sky and to change the focus of the Survey science from that of cosmology, large-scale structure, and galaxy studies to one concentrating more on the structure of our own Milky Way Galaxy. As sky coverage increases with these new initiatives, so will the coverage of good astrometry for faint stars.

IMPACT/APPLICATION

In the area of precise time and time interval the stability of the Master Clock is now about 1 ns rms/day. This stability will be improved by two orders of magnitude through the use of a Rubidium Fountain. This development will lead to time performance at the 100 picosecond level. Improvements in time transfer at this level are also being developed via GPS carrier phase time transfer, GPS receiver and antenna technology, and the WAAS. With this long-term stability and accuracy in time it appears promising to achieve worldwide time stability on the nanosecond level and the resulting accuracy in navigation and targeting of precise munitions should approach the one-meter level. In the area of astrometry, the development of large format CCD focal plane arrays will bring forward the determination of precise positions of a large number of stars. Space astrometry will yield the precise positions of stars at the submicroarcsecond. These star positions are needed for present and future DoD space operations. This will allow these objects to be employed for the precise determination of satellite positions, improved geolocation, and space navigation.

TRANSITIONS

Due to the unique role of the USNO as the standard for Navy and DoD PTTI operations, every successful exploratory development study leads immediately to an improved operational capability. As was stated last year the 6.2 technology development emphasis is shifting to developing improved time standards and time transfer. Unfortunately the development of fountain technology and the later development of optical clocks will be delayed or not take place at all due to a lack of 6.2 funding. Successful development of the TTR12 receiver has improved GPS time. In the area of earth orientation parameters, the determination of UT1 and polar motion has transitioned from 6.2, via 6.4 into operations.

RELATED PROJECTS

This research is highly coordinated with work performed nationally and internationally. The clock work is coordinated with programs at NIST in the US, BIPM, LPTF and Ecole Normal Superior in France and the PTB in Germany. The astrometry work is coordinated with research at universities and national facilities such as the National Radio Astronomy Observatory (NRAO) and the National Optical Astronomy Observatory (NOAO). For example, the program to develop the InSb detector array is a joint effort with NOAO. The development of large focal plane arrays for astrometry at optical wavelengths is being pursued in a joint program, the SDSS with the Astrophysical Research Consortium (Princeton University, The University of Chicago, The Johns Hopkins University, the University of Washington, New Mexico State University, the Max Planck Institute for Astronomy, Astrophysics and Extra-Terrestrial Physics, the University of Pittsburgh, Fermilab).

PUBLICATIONS

Bernardi, M., et al., “Early-Type Galaxies in the Sloan Digital Sky Survey. I. The Sample,” AJ, 125, 1817 (2003).

Bernardi, M., et al., “Early-Type Galaxies in the Sloan Digital Sky Survey II. Correlations between Observables,” AJ, 125, 1849 (2003).

Bernardi, M., et al., “Early-Type Galaxies in the Sloan Digital Sky Survey III. The Fundamental Plane,” AJ, 125, 1866 (2003).

Bernardi, M., et al., “Early-Type Galaxies in the Sloan Digital Sky Survey. IV. Colors and Chemical Evolution,” AJ, 125, 1882 (2003).

Connolly, A. J., et al., “The Angular Correlation Function of Galaxies from Early Sloan Digital Sky Survey Data,” AJ, 579, 42 (2002).

Eisenstein, D. J., et al., “Average Spectra of Massive Galaxies in the Sloan Digital Sky Survey,” AJ, 585, 694 (2003).

Hall, P. B., et al., “Unusual Broad Absorption Line Quasars from the Sloan Digital Sky Survey,” AJ, 141, 267 (2002).

Hogg, D. W., et al., “The Luminosity Density of Red Galaxies,” AJ, 124, 646 (2002).

Ivezić, Ž., et al., “Optical and Radio Properties of Extragalactic Sources Observed by the First Survey and the Sloan Digital Sky Survey,” AJ, 124, 2364 (2002).

Jurić, M., et al., “Comparison of Positions and Magnitudes of Asteroids Observed in the Sloan Digital Sky Survey with those Predicted for Known Asteroids,” AJ, 124, 1776 (2002).

Kauffmann, G., et al., “Stellar Masses and Star Formation Histories for 105 Galaxies from the Sloan Digital Sky Survey,” Mon. Not. Royal Astron. Soc. 341, 33 (2003).

Margon, B., et al., “Faint High-Latitude Carbon Stars Discovered by the Sloan Digital Sky Survey: Methods and Initial Results,” *AJ*, 124, 1651 (2002).

Matsakis, D., “Time and Frequency Activities at the U.S. Naval Observatory,” in *Proceedings of the 34th Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting*, held 3-5 December 2002 in Reston, Virginia, edited by L. A. Breakiron (Washington, D.C.: U.S. Naval Observatory), p. 437 (2003).

Matsakis, D., “Timekeeping at the US Naval Observatory,” *IEEE Aerospace Elec. Sys. Mag.* 18/6 (June), 9 (2003).

Matsakis, D., “Timekeeping at the US Naval Observatory,” *IEEE Aerospace Elec. Sys. Mag.* 18/6 (June), 9(2003).

Pier, J. R., et al., “Astrometric Calibration of the Sloan Digital Sky Survey,” *AJ*, 125, 1559 (2003).

Rockosi, C. M., et al., “Sloan Digital Sky Survey Imaging Camera: Design and Performance,” in *Survey and other Telescope Technologies and Discoveries, Proceedings of the Society of Photo-optical Instrumentation Engineers* held in Waikoloa, Hawaii, 27-28 August 002, edited by J. A. Tyson and S. Wolff (Bellingham, Wash., SPIE Proceedings 4836), p. 180 (2002).

Schmidt, L., Breakiron, L. A., and Ekstrom, C., “Fractional Difference Prewhitening in Atomic Clock Modeling,” in *Proceedings of the 34th Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting*, held 3-5 December 2002 in Reston, Virginia, edited by L. A. Breakiron (Washington, D.C.: U.S. Naval Observatory), p. 473 (2003).

Scranton, R., et al., “Analysis of Systematic Effects and Statistical Uncertainties in Angular Clustering of Galaxies from Early Sloan Digital Sky Survey Data,” *AJ*, 579, 48 (2003).

Strauss, M. A., et al., “Spectroscopic Target Selection in the Sloan Digital Sky Survey: the Main Galaxy Sample,” *AJ*, 124, 1810 (2002).

Szkody, P., et al., “Two Rare Magnetic Cataclysmic Variables with Extreme Cyclotron Features Identified in the Sloan Digital Sky Survey,” *AJ*, 583, 902 (2003).

Vanden Berk, et al., “SDSS J124602.54 + 011318.8: A Highly Luminous Optical Transient at $z = 0.385^1$,” *AJ*, 576, 673 (2002).